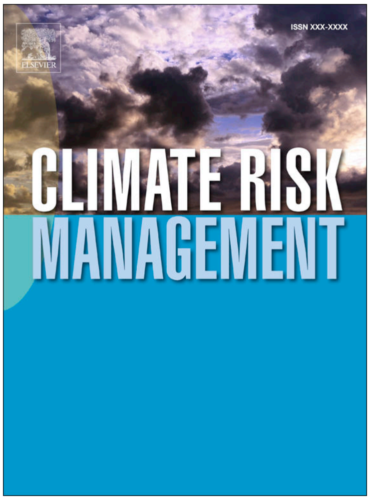

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Assessing the risk of climate change to aquaculture: a national-scale case study for the Sultanate of Oman

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Highlights

- Aquaculture is crucial for world food security yet climate change causes many risks
- We provide a framework for assessing risks from climate change to aquaculture
- Oman aims to expand aquaculture but is also in one of the hottest regions on earth
- We identify key risks to aquaculture in Oman along with adaptation options
- This aquaculture climate risk assessment is readily applicable to any other country

Abstract

Aquaculture is expanding globally and is an increasingly important component of world food security. However, climate change can impact aquaculture through a variety of mechanisms varying by location and aquaculture type with implications for future productivity. Understanding the risks that climate change poses on different culture systems in different locations is important to enable the design of targeted adaptation and resilience building actions.

Here we present an aquaculture climate risk assessment framework, applied to the aquaculture sector of the Sultanate of Oman, that identifies the sensitivity and exposure of different components of the sector to climate change risk.

Oman has aspirations to significantly expand aquaculture over the next decade focussing on coastal shrimp ponds, finfish sea cages, land-based recirculating aquaculture systems, and ponds and raceways. We quantify overall climate risk as the combination of four risks: (1) species' temperature sensitivity, (2) flooding and storm surge exposure, (3) low-oxygen hazard and (4) disease vulnerability. Shrimp culture is identified as highest risk due to high exposure of shrimp ponds to flooding and storm surges, and high disease vulnerability. Seabream cage farming also faces high risk due to high thermal sensitivity and high potential of low-oxygen levels affecting sea cages. Following the risk assessment a stakeholder workshop was conducted to identify targeted adaptation measures for the different components of the sector. The framework for assessing climate risk to aquaculture demonstrated here is equally applicable at the regional, national or sub-national scale to support design of targeted resilience building actions and enhance food security.

Key words: climate adaptation – aquaculture – climate resilience – climate risk assessment – food security – Sultanate of Oman – seabream culture – shrimp culture

1. Introduction

Aquaculture is a rapidly expanding component of global food security, and in 2018 overtook wild harvest fisheries in its contribution to global human food supply (FAO, 2020). This importance is expected to significantly grow over the coming decades as the world population, and prevalence of seafood in people's diets, continue to rise (Troell et al., 2014; Jennings et al., 2016; Shepon et al., 2021). This is particularly so as global aquaculture output has consistently grown over the last 20 years (Little et al., 2016; FAO, 2020) whilst wild harvest fisheries show little opportunity for expansion with over 90% of stocks considered either maximally sustainably fished, or overfished (60% and 34% respectively; FAO 2020). Aquaculture of marine species is an important part of total aquaculture production, accounting for over 50% of global aquaculture production by weight, albeit comprising a smaller contribution to total human food production from aquaculture (FAO, 2020).

Beyond food security, aquaculture also plays an increasingly important role in the livelihoods, employment and economic development of many communities especially in developing countries; in 2018 over 20 million people were engaged in the sector globally (FAO, 2020). However although growing in importance for world food security and economic development, aquaculture is susceptible to climate change (Callaway et al., 2012; Soto et al., 2018; Poulain et al., 2018; Pernet and Browman, 2021). So it is important to assess the risks and challenges that climate change poses to aquaculture in order to implement targeted adaptation and resilience building actions to safeguard future productivity.

Climate change is impacting on world aquaculture in multiple ways (Callaway et al., 2012; Gubbins et al., 2013; Soto et al., 2018). Although rising water temperatures can benefit growth rates of some species, this may also push species beyond their thermal limits; hot summers can lead to heat stress, notably for cold-water species that include some of the world's most important aquaculture species (Gubbins et al., 2013). Low-oxygen levels (hypoxia) are becoming more common and may cause 'fish kills' especially where fish are reared in dense conditions as in sea pens (Araújo-Luna et al., 2018). Rising sea levels combined with increasing storminess (Walsh et al., 2017; Sainsbury et al., 2021) are exacerbating the risk of storm surges that can affect coastal culture systems and infrastructure. Disease outbreaks are a major risk factor affecting global aquaculture production (Stentiford et al., 2021) and warming increases chances of outbreaks (Leung and Bates, 2013; Burge et al., 2014). Ocean acidification can be detrimental for mollusc spat-fall making natural seeding of mollusc farms less efficient; and warmer waters may facilitate the establishment of invasive species in new areas (Gubbins et al., 2013). While climate change may also create opportunities (Bergh et al., 2007), on balance there could be serious repercussions to the aquaculture sectors of many countries, and the risks could be widely different depending on culture type and location (Pernet and Browman, 2021) with warmer countries likely to be impacted more (Soto et al., 2018).

In the Sultanate of Oman the aquaculture sector is at an early stage of development with commercial production having grown modestly from 13 t in 1998 to 450 t in 2018 (FAO, 2018). However, the sector has been identified for major expansion within Oman's national economic diversification programme to support economic development and food security in decades to come (MAFW, 2019). The national economic development programme lays out the objective to expand aquaculture production to over 200,000 t per year, generating over US$ 500 million annually by the end of the decade based on a major governmental and private sector investment programme of over US$ 1.5 billion (MAFW, 2019; Peeler and Scott 2018; Table 1). Furthermore, aquaculture could help reduce pressure on wild stocks (Al-Rashdi et al., 2011), and enable restocking of locally overexploited sea cucumber and abalone populations (Al-Rashdi and Iwao, 2008; Al-Rashdi et al., 2019). The government plans for development of the aquaculture sector focus on coastal shrimp ponds, finfish sea cages especially for seabream, recirculating aquaculture systems (RAS) for groupers and salmon, and ponds and raceways for sea cucumber and the endemic abalone *Haliotis mariae* (MAFW, 2019; and see Figure 1).

However, Oman is situated in one of the hottest regions on earth, and climate change is progressively developing in the north-western Indian Ocean and Arabian Gulf at the same time as the development of Oman's aquaculture sector (Piontkovski and Al-Oufi, 2015; Piontkovsky and Queste, 2016; Noori et al., 2019; ROPME, 2020). The primary impacts in the region that could affect aquaculture are increasing sea temperatures, large-scale hypoxia events, and increases in cyclones and storm surges (ROPME, 2021). Due to the major expansion planned for aquaculture in Oman, evaluating the nature of these risks to the different components of the sector is necessary to inform design of targeted adaptation and resilience actions to safeguard future production and investments in the sector.

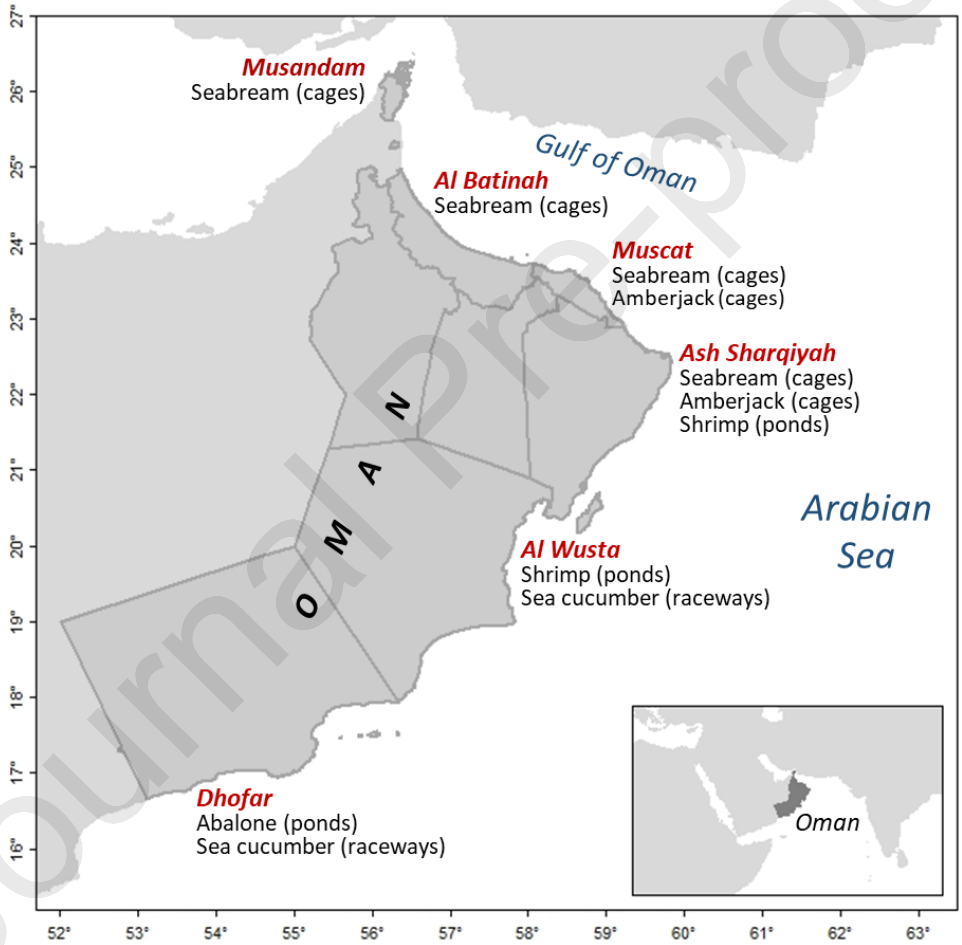

Figure 1. Map of the Sultanate of Oman showing the six coastal governorates assessed here. For each governorate (red font) the most important current or planned types of aquaculture are indicated. For some planned culture types (RAS, oyster culture) no information on designated sites was available. Inset map shows location of Oman within the wider region.

This study presents a climate risk assessment (CRA) of the aquaculture sector of Oman. It builds on the CRA introduced by the Intergovernmental Panel on Climate Change in 2014 as a means for quantifying climate change risks to linked ecological-economic systems (IPCC, 2104). This is a modified version of the earlier, climate vulnerability assessment (CVA) framework originally introduced in 2001 (IPCC, 2001), where 'climate vulnerability' is quantified based on the combination of exposure, sensitivity and adaptive capacity. In the revised CRA framework – developed to better capture risk and (actionable) risk management, and removing focus from vulnerability – climate risk is quantified as the combination of hazard, exposure or sensitivity, and vulnerability. This identification of the main sources of risk, and how these differ between sectors, communities or regions, allows for informed decisions on actions to reduce risk and build resilience to climate change (Poulain et al., 2018).

For wild capture fisheries, several studies on climate risk have been carried out using either the CVA or CRA frameworks at the global and regional scale (e.g. Allison et al., 2009; Monnereau et al., 2017), or as small-scale, localised studies (e.g. Pinnegar et al., 2019). In contrast, for aquaculture few climate risk assessments have been conducted (but for a global, country-level comparison, see Handisyde et al., 2017). This may be because aquaculture is seen as less immediately impacted by weather, climate, and external environmental fluctuations than fisheries. Nevertheless, the world's growing reliance on aquaculture for food security and the manifold potential impacts of climate change on aquaculture necessitate an equal focus for the application of CRAs to aquaculture. There is clearly an urgent need for a simple framework that could be rolled out at multiple scales from individual farms to global regions, drawing on international best practice (Poulain et al., 2018).

Here we develop and apply an aquaculture climate risk assessment at a national scale to the developing aquaculture sector in Oman. We define overall climate risk as the combination of four primary components of climate risk that have been identified for the aquaculture sector in Oman. The risk components are assessed for each of the major currently cultured species and for the key candidate species being considered for future development; where possible, risks are evaluated spatially across Oman's coastal governorates. The purpose of this study is identification of the key climate risks to support design and prioritisation of adaptation actions aimed at reducing, anticipating, or mitigating the potential challenges from climate change.

2. Methods

2.1. *Overall approach*

As aquaculture in Oman is in an early stage of development, this CRA was based on expectations of future development in the sector. It takes account of aspirations to grow the industry rapidly to a regionally leading position (MAFW, 2019), both from a socio-economic perspective to generate revenue and enhance food security, and from an environmentally sustainable perspective. While a growing body of research on Omani aquaculture exists (e.g. Al-Rashdi and Iwao 2008; Al-Rashdi et al. 2011, 2018), including on disease risk (Peeler and Scott 2018), the focus here is on risk factors known to be associated with climate change.

In this CRA, the calculation of climate risk for aquaculture is based on four components:

1. *Thermal sensitivity*, which compares the optimum growing temperatures of different species cultured, in relation to average sea temperatures characterising each governorate;
2. *Flooding and storm surge exposure*, the vulnerability to coastal flooding and storm surge of different culture types in different governorates;
3. *Low-oxygen hazard*, associated with the likelihood of cultured species being exposed to low-oxygen water conditions, taking into account the culture methods; and
4. *Disease vulnerability*, potential exposure to significant diseases (based on the number of diseases of concern reported for each species and the culture method used).

For each component, the risk index is calculated based on the sensitivity of each species cultured to the risk factor and the expected exposure to the risk in each governorate. A measure of *overall climate risk* – by species and governorate – is then calculated as the unweighted mean of the four components (Figure 2).

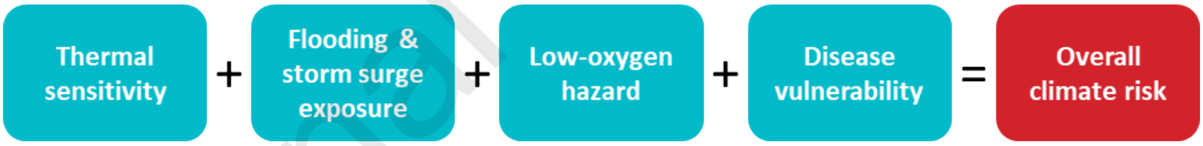

Figure 2. The four components of risk used in the present CRA which combine to form overall climate risk to aquaculture in Oman.

The outputs of the risk assessment were then presented in a stakeholder workshop and used as the basis for designing practical adaptation actions.

2.2. Selection of species

The species included were derived from Peeler and Scott (2018) who compiled information on planned developments of aquaculture for different species in Oman. Table 1 summarises the species included, along with their expected potential for development within the aquaculture sector of Oman, the main culture systems, and the governorates where these are either produced or are foreseen to be produced.

Table 1. Overview of species included based on current and potential future importance for Oman aquaculture, including information on current or proposed culture type and projected production (based on Peeler and Scott 2018; supplementary data for cobia taken from Prins 2015). Price per kg and projected value are expressed in 2018-US$ and based on mean global aquaculture price (from FAO Fisheries and Aquaculture Statistics). Projected value by 2023 is based on projected production (Peeler and Scott 2018). Figures on future production should only be seen as indicative of proposed future development.

Species group	Species	Type of culture	Projected production (t)	Price/kg (US$)	Projected value (US$)	Regions
Seabreams	Gilthead seabream *Sparus aurata*	Marine cages; RAS	15500	$4.73	$143,500,000	Musandam, Muscat, Ash Sharqiyah
	Sobaity seabream *Sparidentex hasta*			$13.25		Musandam, Muscat, Ash Sharqiyah
	Goldlined seabream *Rhabdosargus sarba*			$9.79		Musandam, Muscat, Ash Sharqiyah
Groupers	Yellowfin hind (grouper) *Cephalopholis hemistiktos*	RAS	9000	$18.59	$167,300,000	not specified
	Greasy grouper *Epinephelus tauvina*			$18.59		not specified
Asian seabass	Asian seabass (Barramundi) *Lates calcarifer*	Marine cages	2500	$4.52	$11,300,000	not specified
Amberjacks	Japanese amberjack *Seriola quinqueradiata*	Marine cages	2000	$7.77	$19,660,000	Muscat, Ash Sharqiyah, Al Wusta
	Greater amberjack *Seriola dumerili*			$9.10		Muscat, Ash Sharqiyah, Al Wusta
	Yellowtail amberjack *Seriola lalandi*			$12.62		Muscat, Sharqiyah, Al Wusta
Cobia	Cobia *Rachycentron canadum*	Marine cages		$2.83		not specified
Red snapper	Red snapper (Hamra) *Lutjanus malabaricus*	Marine cages	100	$6.62	$662,000	not specified
Pompano	Scubnose pompano *Trachinotus blochii*	Marine cages	100	$4.77	$477,000	not specified
Atlantic salmon	Atlantic salmon *Salmo salar*	RAS	20000	$7.07	$141,400,000	not specified
Shrimp	Indian white prawn *Penaeus indicus*	Shrimp ponds	130000	$4.92	$840,700,000	Ash Sharqiyah, Al Wusta
	Whiteleg shrimp *Penaeus vannamei*			$6.09		Ash Sharqiyah, Al Wusta
	Giant tiger prawn *Penaeus monodon*			$8.39		Ash Sharqiyah, Al Wusta
Abalone	Oman abalone *Haliotis mariae*	RAS and restocking	2000	$11.30	$22,600,000	Dhofar
Oyster	Hooded oyster *Saccostrea cucullata*			$10.31		not specified
	Mangrove cupped oyster *Crassostrea rhizophorae*			$1.00		not specified
Sea cucumber	Sandfish sea cucumber *Holothuria scabra*	Marine ponds and raceways restocking	2000	$5.27	$10,540,000	Al Wusta

2.3. Sensitivity to thermal stress

For each species, the sensitivity to thermal stress from climate change was assessed. In the study area, sea temperatures are already high compared to most species' observed temperature tolerance ranges in the wild (cf. Cheung et al., 2013), and are expected to rise further. In this analysis, thermal sensitivity takes account of species' upper temperature tolerance ranges, in relation to sea temperatures characterising each governorate.

Information on species' temperature preferences was taken from Aquamaps (accessed July–September 2020), where modelled 'native range data' for species were collated (www.aquamaps.org; Kaschner et al., 2016). This is based on long-term annual mean sea temperature for all half-degree latitude–longitude grid cells, where a given species has been "observed" according to OBIS or GBIF species occurrence records. Where multiple modelled maps were available for a species in Aquamaps, the most recent update was selected. To describe the species' upper temperature tolerance, data on their 'maximum preferred temperature' (TP90) were downloaded (following Pinnegar et al., 2019). TP90 is defined as the 90th percentile temperature, based on sea surface temperatures in the observed distribution range of the species in the wild. Thus, for a given species' wild population, it may be assumed that 90% of individuals occur in areas with annual mean sea temperatures below TP90.

We then combined each species' TP90 with annual mean sea surface temperature (SST) data for the waters adjacent to each governorate, to calculate the 'thermal safety margin' (TSM: see Payne et al., 2021) within that region, as the difference between TP90 and SST. If TSM is positive, the species' maximum preferred temperature is higher than the mean annual SST, indicating the species is unlikely to suffer substantially from thermal stress if held under ambient conditions. If TSM is negative, mean ambient temperatures in the governorate are beyond the species' optimal thermal tolerance ranges; if held under ambient conditions these species are likely to be at risk of thermal stress particularly during the warmer season(s).

2.4. Exposure to flooding and storm surge

For each species and per governorate, a measure of exposure to coastal flooding and storm surge was calculated, associated with sea level rise and tropical cyclones. This took account of both inherent differences between culture types in exposure to flooding, and of topological differences between governorates (Fritz et al., 2010; Al-Buloshi et al., 2014; Hereher et al., 2020).

Firstly, for each species a *sensitivity score to flooding and storm surge* was defined as 1 (low), 2 (medium) or 3 (high), based on culture type and biological characteristics. Species typically reared in floating sea cages were scored as having 'low' sensitivity as these facilities are not directly impacted by flooding or coastal inundation (although extreme weather could lead to losses particularly if cages are inadequately engineered). Species cultured in ponds or raceways (e.g. shrimps, sea cucumbers), often located in low-lying terrain close to the sea and prone to inundation, were scored as having 'high' sensitivity. Species reared in RAS were scored as having 'medium' sensitivity as these are typically connected with coastal areas.

Secondly, for each coastal governorate a *flooding hazard score* was calculated, using the area (per km coastline) predicted to be flooded if mean sea level rises by 0.2 m; this was based on Al-Buloshi et al. (2014) who simulated impacts of climate change-related sea level rise and coastal flooding on Oman. For each species and per governorate, *exposure to flooding and storm surge* was then calculated as cultured species' *sensitivity to flooding* x governorates' *flood hazard*.

2.5. Hazard from low-oxygen levels

Given Oman's proximity to the world's largest, naturally occurring marine low-oxygen zone (Acharya and Panigrahi, 2016), the potential for low-oxygen levels in seawater is seen as an important risk factor to the sector. Prevalence of hypoxia in the Arabian Sea has increased since the 1970s (Piontkovski and Al-Oufi 2015; Piontkovski and Queste, 2016; Queste et al., 2018), a trend expected to continue with warming. For each aquaculture species and per governorate, a measure of *hazard from low-oxygen levels* was scored, associated with the likelihood of cultured species being exposed to low-oxygen water conditions in particular areas, taking into account the culture methods.

Firstly, for each species *sensitivity to low-oxygen conditions* was scored, considered highest (score 3) in fast-swimming fishes (e.g. seabream, seabass) with high oxygen demands, and lowest in sessile species such as oysters which have lower oxygen demands (score 1). Furthermore, the type of culture is also of relevance and was here included in 'species sensitivity'; fish held under fully controlled RAS are unlikely to be impacted (score 1), whereas species held in sea cages would be directly impacted by low-oxygen seawater and may suffer extensive mortalities. Species where re-stocking takes place (abalone, sea cucumber) are considered to have intermediate sensitivity (score 2), and likewise salmon, which although planned to be held in RAS, have high oxygen requirements.

Secondly, each governorate was rated a *low-oxygen hazard* score. In southern governorates coastal ecosystems are subject to extensive seasonal upwelling during the summer monsoon, and oxygen levels may drop substantially. Hypoxic conditions are less likely further north (such as in Ash Sharqiyah) and are rare (albeit not fully absent) in the northernmost governorates (Piontkovski and Al-Oufi 2015; Piontkovski and Queste, 2016). Reflecting these differences, governoraties' low-oxygen hazard was scored between 1 (lowest) and 4 (highest). For each species and per governorate, the overall *hazard from low-oxygen levels* was then calculated as species' *low-oxygen sensitivity* x governorates' *low-oxygen hazard.*

2.6. Vulnerability to disease

Globally, diseases are a primary driver of successes or losses in aquaculture, with the FAO estimating least US$ 6 billion in annual losses from aquaculture yield (Jennings et al., 2016). Certain diseases are particularly prominent: white spot disease in shrimp has caused losses exceeding $1 billion per annum since the 1990s (Stentiford et al., 2012). Emergent issues include microsporidiosis in seabream which can stunt growth, with limited scope for treatment (Palenzuela et al. 2014). Disease risk is incorporated into this CRA as it may increase with climate change due to two factors. First, in a warming world the geographic distribution of diseases in the wild may change, leading to farmed species being exposing to new diseases. Second, if farmed animals become thermally stressed they can become immunocompromised and more susceptible to disease.

Our analysis draws on the list of fish, molluscan and crustacean diseases considered high priority risk factors in Oman and recommended for surveillance and listing in national legislation (Table 3 in Peeler and Scott, 2018). Their list combines information on the expected level of production of aquaculture species in Oman, with information on aquatic animal diseases per species as listed by the World Organisation for Animal Health (OIE, formerly Office International des Epizooties).

In the present analysis, proxies for *disease-related vulnerability* for Oman aquaculture species were calculated as the average of three separate risk factors. These included, firstly, the total number of OIE listed aquatic diseases per species (Peeler and Scott, 2018), including viral, bacterial and fungal diseases. We regard this as a useful indicator of the breadth of disease risk but caution against its over-interpretation, its inclusion is warranted on pragmatic grounds. The second disease risk factor relates to the origin of broodstock (following Doubleday et al., 2013), and is ranked 1 if all aquaculture stock is derived from local broodstock (and hence the risk of pathogen import is low); 2 if derived from a combination of local and imported broodstock; and 3 if fully derived from imported broodstock (and hence the risk of pathogen import is high). The third risk factor is based on concentration of production, where having multiple, spatially separated farms as opposed to a single farm is seen as lower risk to overall production (Peeler and Scott, 2018). This risk factor was also ranked 1 to 3 (1, production expected over at least 5 farms, hence low risk; 2, production in 2-4 farms, hence medium risk; 3, concentrated in a single farm, hence high risk).

2.7. Overall climate risk

Our assessment of *overall climate risk* to Oman aquaculture species in each of the coastal governorates combines the above four risk components. Of these, information for three components – (1) thermal sensitivity, (2) exposure to flooding and storm surge, and (3) low-oxygen hazard – is spatially disaggregated by governorate. In the case of (4) disease vulnerability, a single risk metric across all governorates is available per species. Following several other climate risk analyses (e.g., Monnereau et al., 2017; Pinnegar et al., 2019; Payne et al., 2021), the values for each of the four risk components were re-scaled between 0 and 1 (from lowest to highest risk). Following re-scaling, the *overall climate risk* (per species, per governorate) was then calculated as the unweighted mean of the four components.

2.8. Stakeholder workshop aimed at identifying adaptation options

The purpose of this paper is to present the risk assessment framework, but the outputs were then presented at an online stakeholder workshop to identify potential priority adaptation actions for the aquaculture sector of Oman. The workshop was held on 8–9 December 2020, with 21 participants selected from across government, science, and the seafood sector, as recommended by officers within the Ministry of Agriculture, Fisheries and Water Resources. Insights from workshop participants were used to validate the results and help identify priority adaptation actions, making use of the framework of the FAO 'climate adaptation toolbox' (Poulain et al., 2018; FAO, 2019). Accordingly, *preventative* adaptation options were identified aimed at *reducing the risk of impacts from* climate change, i.e. at preventing the event from happening; and *mitigative* adaptation options aimed at *reducing or mitigating the consequences* if an event were to happen.

3. Results

3.1. Thermal sensitivity

The 19 aquaculture species that may be farmed in ambient conditions differ widely in maximum preferred temperatures (TP90), ranging from 21.44°C in gilthead seabream to 29.77°C in yellowfin hind (Table 2). Between Oman's coastal governorates, there is also variation in SST, which averaged over the year is warmer in northern than southern coastal sea areas. In combination, species differences in TP90 and spatial differences in SST are reflected in thermal safety margins for candidate species that vary considerably, from positive (ambient SST < species' TP90, i.e. low thermal stress; shaded blue in Table 2) to highly negative (ambient SST > species' TP90, i.e. high thermal stress; shaded red).

Atlantic salmon have a very low maximum preferred temperature (12.77°C) compared to ambient conditions in Oman however the plans are to grow salmon in fully enclosed refrigerated RAS. In this case, the thermal risk factor is not included in further analysis of climate risk.

Among the species reared under ambient conditions in Oman, gilthead seabream has negative thermal safety margins in all governorates and particularly in the north, indicating thermally stressful conditions for this species which is not endemic to Oman. Despite this, it is currently cultured commercially in marine cages in Muscat Governorate, with further developments planned across multiple governorates. By contrast, two seabream species indigenous to Omani waters so far only cage-cultured at minor scale – goldlined and sobaity seabream (both TP90 >28°C) – show thermal safety margins that may be considered in line with ambient conditions for Oman (especially in Ash Sharqiyah, and further south), indicating low risk of thermal stress if cultured.

Thermal risk is assessed as low for barramundi, cobia, red snapper or pompano held in ambient-temperature cage culture. Of three amberjack species considered, two – yellowtail and greater amberjack – are found at low thermal risk, with thermal safety margins either positive or close to zero. However, Japanese amberjack is at fairly high thermal risk if held in ambient-temperature cages. While yellowfin hind and greasy grouper would be held in controlled RAS not exposed to ambient temperature conditions as in sea cages, both are within natural temperature conditions in Omani waters.

Each of the three shrimp species considered have high TP90 (>29°C) with positive thermal safety margins for all governorates indicating low risk of thermal stress, in particular for Ash Sharqiyah and Al Wusta where production is planned. For Oman abalone, ambient conditions in Dhofar (where currently cultured) are within the species' thermal preferences; this is also the case for sand fish sea cucumber in Al Wusta (where production takes place).

Table 2. Risk from *thermal sensitivity*. The 'maximum preferred temperatures' (TP90) for 20 target or candidate aquaculture species in Oman, as well as – shown separately for each governorate – the 'thermal safety margins.' Annual mean SST for coastal waters adjacent to each governorate is indicated (bottom of table). Thermal safety margins are defined as the difference between a species' TP90 and governorate's SST, in °C (TP90 – SST), colour-coded from blue to red (low to high risk). Figures in bold indicate actual or planned developments. *Note:* for Atlantic salmon, which in Oman is planned to be cultured in fully temperature-controlled RAS, thermal sensitivity margins are shown but no risk-based colour-shading applied.

			Species' thermal sensitivity margin by governorate (annual mean SST in °C above TP90)					
Species group	**Species**	**Maximum preferred temperature (TP90, °C)**	**Musan-dam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**
Seabreams	Gilthead seabream *Sparus aurata*	21.44	***-7.42***	-7.31	***-7.18***	***-5.66***	-4.96	-5.57
	Sobaity seabream *Sparidentex hasta*	28.24	***-0.62***	-0.51	***-0.38***	***1.14***	1.84	1.23
	Goldlined seabream *Rhabdosargus sarba*	28.43	***-0.43***	-0.32	***-0.19***	***1.33***	2.03	1.42
Groupers	Yellowfin hind (grouper) *Cephalopholis hemistiktos*	29.77	0.91	1.02	1.15	2.67	3.37	2.76
	Greasy grouper *Epinephelus tauvina*	29.15	0.29	0.40	0.53	2.05	2.75	2.14
Asian seabass	Asian seabass *Lates calcarifer*	28.89	0.03	0.14	0.27	1.79	2.49	1.88
Amber-jacks	Japanese amberjack *Seriola quinqueradiata*	24.73	-4.13	-4.02	***-3.89***	***-2.37***	***-1.67***	-2.28
	Greater amberjack *Seriola dumerili*	28.23	-0.63	-0.52	***-0.39***	***1.13***	***1.83***	1.22
	Yellowtail amberjack *Seriola lalandi*	27.79	-1.07	-0.96	***-0.83***	***0.69***	***1.39***	0.78
Cobia	Cobia *Rachycentron canadum*	28.77	-0.09	0.02	0.15	1.67	2.37	1.76
Red snapper	Red snapper *Lutjanus malabaricus*	28.84	-0.02	0.09	0.22	1.74	2.44	1.83
Pompano	Scubnose pompano *Trachinotus blochii*	29.12	0.26	0.37	0.50	2.02	2.72	2.11
Atlantic salmon	Atlantic salmon *Salmo salar*	12.77	(-16.09)	(-15.98)	(-15.85)	(-14.33)	(-13.63)	(-14.24)
Shrimp	Indian white prawn *Penaeus indicus*	29.18	0.32	0.43	0.56	***2.08***	***2.78***	2.17
	Whiteleg shrimp *Penaeus vannamei*	29.08	0.22	0.33	0.46	***1.98***	***2.68***	2.07
	Giant tiger prawn *Penaeus monodon*	29.10	0.24	0.35	0.48	***2.00***	***2.70***	2.09
Abalone	Oman abalone *Haliotis mariae*	27.50	-1.36	-1.25	-1.12	0.40	1.10	***0.49***
Oyster	Hooded oyster *Saccostrea cucullata*	29.12	0.26	0.37	0.50	2.02	2.72	2.11
	Mangrove cupped oyster *Crassostrea rhizophorae*	28.19	-0.67	-0.56	-0.43	1.09	1.79	1.18
Sea cucumber	Sandfish sea cucumber *Holothuria scabra*	29.27	0.41	0.52	0.65	2.17	***2.87***	2.26
Annual mean SST by governorate (°C)			**28.86**	**28.75**	**28.62**	**27.10**	**26.40**	**27.01**

3.2. *Exposure to flooding and storm surge*

Shrimp culture is assessed as being at high risk from sea level rise and flooding (Table 3), particularly in Al Batinah, Muscat and Ash Sharqiyah – the latter governorate important for current shrimp production. For Al Wusta, where production is also envisaged, the exposure scores are not as high, noting however that within this governorate, suitable locations for shrimp ponds would likely be in low-lying areas, hence more prone to flooding. Exposure to flooding and storm surge is, likewise, high for sea cucumbers owing to the culture in coastal raceways, typically in low-lying terrain.

Flooding exposure is assessed as intermediate for groupers and Atlantic salmon cultured in RAS facilities, which have controlled environmental conditions but typically are located in coastal zones.

This risk factor is low for species farmed in floating sea cages (seabreams, amberjacks, Asian seabass; Table 3), and for the northern governorate of Musandam; the steep coastal topography and many deep sheltered bays (khawrs) appear to render Oman's northernmost governorate least susceptible to losses from this hazard.

Table 3. Relative exposure to *flooding and storm surge*, assessed for Oman key aquaculture species or species groups by governorate. For each species, *sensitivity to flooding* is scored (1 low, 3 high) based on culture type and biological characteristics. For each governorate, *flooding hazard* is scored (bottom row) based on the area predicted to be flooded if mean sea level rises by 0.2 m (Al-Buloshi et al., 2014) per km of coastline. Relative exposure per species and governorate is then calculated as *sensitivity x hazard*. Colour-shading indicates low (light) to high exposure (dark red). Figures in bold indicate actual or planned developments.

		Species' relative exposure by governorate					
Species or species group	**Sensitivity to flooding**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**
Seabreams	1	***0.07***	0.25	***0.26***	***0.25***	0.18	0.05
Groupers	2	0.14	0.50	0.51	0.50	0.36	0.10
Asian seabass	1	0.07	0.25	0.26	0.25	0.18	0.05
Amberjacks	1	0.07	0.25	***0.26***	***0.25***	***0.18***	0.05
Cobia	1	0.07	0.25	0.26	0.25	0.18	0.05
Red snapper	1	0.07	0.25	0.26	0.25	0.18	0.05
Pompano	1	0.07	0.25	0.26	0.25	0.18	0.05
Atlantic salmon	2	0.14	0.50	0.51	0.50	0.36	0.10
Shrimp	3	0.21	0.75	0.77	***0.75***	***0.54***	0.14
Oman abalone	2	0.14	0.50	0.51	0.50	0.36	***0.10***
Oysters	1	0.07	0.25	0.26	0.25	0.18	0.05
Sea cucumber	3	0.21	0.75	0.77	0.75	***0.54***	0.14
Inundated area (km²) with sea level rise 0.2 m		35	60	50	120	105	25
Coastline (km)		495	241	196	480	584	523
Flooding hazard: inundated area (km²) per km of coastline with sea level rise 0.2 m		0.07	0.25	0.26	0.25	0.18	0.05

3.3. *Hazard from low-oxygen levels*

The hazard from low-oxygen levels in sea water was assessed as greatest (score 12 on scale 1–12) for fish species cultured in marine cages (seabreams, amberjacks, seabass, cobia), especially in southern governorates (Al Wusta, Dhofar) with coastal waters more likely to be impacted from hypoxic conditions (Table 4). However, most production for these species is envisaged further north where this risk factor is lower.

Low-oxygen hazard is assessed as intermediate (score 8) for abalone and sea cucumber in Dhofar and Al Wusta and would potentially impact these after restocking into the wild. This hazard is assessed as minor for shrimp as these are reared in very shallow coastal ponds that can be aerated, and likewise as minor for oysters owing to the low oxygen demands associated with sessile life style (Table 4). For groupers reared in RAS, low-oxygen hazard is assessed as low owing to the controlled conditions, whereas for Atlantic salmon reared in RAS this hazard is assessed as intermediate owing to the active-swimming behaviour and associated high oxygen demands.

Table 4. Relative hazard from *low-oxygen levels in seawater*, assessed for Oman key aquaculture species or species groups by governorate. For each species, *sensitivity to low-oxygen risk* is scored (1 low, 3 high) based on culture type and biological characteristics. For each governorate, *low-oxygen hazard* is scored (1 low, 4 high), based on geographical patterns in duration and intensity of low-oxygen conditions linked to the Arabian Sea oxygen minimum zone (Acharya and Panigrahi, 2016; Piontkovski and Queste, 2016; Queste et al., 2018). Relative hazard per species and governorate is then calculated as *sensitivity x hazard*. Colour-shading indicates low (light) to high hazard (dark red).

		Species' relative hazard by governorate					
Species or species group	**Sensitivity to low-oxygen risk**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**
Seabreams	3	***3***	3	***6***	***9***	12	12
Groupers	1	1	1	2	3	4	4
Asian seabass	3	3	3	6	9	12	12
Amberjacks	3	3	3	***6***	***9***	***12***	12
Cobia	3	3	3	6	9	12	12
Red snapper	3	3	3	6	9	12	12
Pompano	3	3	3	6	9	12	12
Atlantic salmon	2	2	2	4	6	8	8
Shrimp	1	1	1	2	***3***	***4***	4
Oman abalone	2	2	2	4	6	8	***8***
Oysters	1	1	1	2	3	4	4
Sea cucumber	2	2	2	4	6	***8***	8
Low-oxygen hazard by governorate		1	1	2	3	4	4

3.4. Vulnerability to disease

The culture type ranking highest for disease vulnerability, was shrimp. This reflects the large number (9) of OIE listed diseases for *Penaeus vannamei* and *P. monodon*. For the local, endemic species *P. indicus* only 1 disease type is listed, but this might reflect that it has been researched much less intensively than the two other widely cultivated species. In particular, *P. indicus* is listed as being susceptible to white spot disease – by far the most important shrimp disease in Asia (see Supplementary Table S1). In pond culture, where seawater is brought in, it is difficult to fully exclude disease from ponds; barriers or filters can be incorporated but completely excluding disease vectors remains challenging. Moreover, partial import of shrimp broodstock will likely be required to supplement local broodstock (Peeler and Scott, 2018) further adding to disease vulnerability.

For the three amberjack species (2 OIE listed diseases), import of live broodstock is expected; some import of juveniles is envisaged for grouper culture (3 OIE listed diseases for greasy grouper), which would increase risk of pathogen introduction. Hence disease vulnerability is ranked intermediate for these species (Table 5). Disease vulnerability is ranked low for seabreams with few OIE listed diseases, where production takes place in many different sea cages and is hence not highly concentrated.

For Atlantic salmon, a single RAS facility is expected to come into production in the next 5 years; provided original stock is sourced free of OIE listed diseases, disease risk is likely low even though many diseases have been OIE listed for salmon in colder climates. As Oman does not have endemic salmonid species there is no risk of disease spread from wild populations. Moreover, disease spread from RAS is inherently low (Peeler and Scott 2018). This situation could change if salmon production would expand beyond a few, isolated RAS sites.

We emphasise that interpretation of our disease risk factors requires caution, as many other potential factors could not be included here. These include the severity by which a single type of pathogen may impact stock (which may range from a modest reduction in growth, to mass mortalities in multiple farms); the speed by which pathogens may spread both within and across farms; and the susceptibility of farmed species to diseases that are present in local, wild stocks.

Table 5. Proxies for *vulnerability to disease* (right-most column) for Oman aquaculture species, calculated as the average of three risk factors: (a) total number of OIE listed diseases per species (Peeler and Scott, 2018); (b) origin of broodstock, whether locally produced or imported; and (c) concentration of production in few or many farms. Number of OIE listed diseases combines the viral, bacterial and fungal diseases listed in Supplementary Table S1. Ranking of broodstock-related risk: 1, all stock derived from local broodstock (low risk of pathogen import); 2, stock derived partly from local, partly from imported broodstock (medium risk); 3, fully derived from imported broodstock (high risk of pathogen import). Risk ranking of concentration of production: 1, production spread over at least 5 farms (risk spread, hence lower); 2, production in 2-4 farms; 3, production in 1 farm only (risk concentrated, hence higher). Colour-shading indicates low to high risk.

Species group	**Species**	**Number of OIE listed diseases**	**Local produce or import of broodstock**	**Concen-tration of production**	***Overall vulnerability to disease***
Seabreams	Gilthead seabream *Sparus aurata*	1	1	1	**1.0**
	Sobaity seabream *Sparidentex hasta*	0	1	1	**0.7**
	Goldlined seabream *Rhabdosargus sarba*	1	1	1	**1.0**
Groupers	Yellowfin hind (grouper) *Cephalopholis hemistiktos*	0	2	2	**1.3**
	Greasy grouper *Epinephelus tauvina*	3	2	2	**2.3**
Asian seabass	Asian seabass *Lates calcarifer*	3	1	2	**2.0**
Amber-jacks	Japanese amberjack *Seriola quinqueradiata*	2	3	2	**2.3**
	Greater amberjack *Seriola dumerili*	2	3	2	**2.3**
	Yellowtail amberjack *Seriola lalandi*	2	3	2	**2.3**
Cobia	Cobia *Rachycentron canadum*	0		n.a.	**n.a.**
Red snapper	Red snapper *Lutjanus malabaricus*	0	1	3	**1.3**
Pompano	Scubnose pompano *Trachinotus blochii*	0	1	3	**1.3**
Atlantic salmon	Atlantic salmon *Salmo salar*	0 *)	1	3	**2.0**
Shrimp	Indian white prawn *Penaeus indicus*	1	2	1	**1.3**
	Whiteleg shrimp *Penaeus vannamei*	9	2	1	**4.0**
	Giant tiger prawn *Penaeus monodon*	9	2	1	**4.0**
Abalone	Oman abalone *Haliotis mariae*	3	1	1	**1.7**
Oyster	Hooded oyster *Saccostrea cucullata*	0		n.a.	**n.a.**
	Mangrove cupped oyster *Crassostrea rhizophorae*	0		n.a.	**n.a.**
Sea cucumber	Sandfish sea cucumber *Holothuria scabra*	0	1	2	**1.0**

3.5. Overall climate risk to aquaculture

Overall climate risk to aquaculture in Oman – combining thermal sensitivity, flooding exposure, low-oxygen hazard and disease vulnerability – is highest for shrimp culture (Table 5; for a full description of all component rankings by governorate, see Supplementary Table S2). This is due to (1) high disease vulnerability, and (2) high exposure of coastal shrimp ponds to flooding or storm surge. Flooding exposure is high in Ash Sharqiyah where shrimp culture is being started; it is lower for Al Wusta but within this governorate, sites suitable to shrimp culture would typically be at low elevation and flood risk will depend on the exact location of each facility. For *Penaeus indicus*, overall risk is scored lower than for *P. vannamei* and *P. monodon* due to a smaller number of OIE listed diseases, however as highlighted above, diseases in both other species have been investigated far more extensively, and *P. indicus* is impacted by the important white spot disease. Hence overall climate risk to *P. indicus* might be underestimated here.

Overall climate risk is also high in amberjacks cultured in sea cages, due to (1) exposure to pathogens (with amberjacks being at risk from at least two OIE listed viral diseases) and (2) potential hazard from low-oxygen levels (amberjacks being active swimmers with high oxygen demands). Low-oxygen risk is higher in waters off Al Wusta, during the monsoon season impacted by the Arabian Sea oxygen minimum zone. However, flooding exposure to cage-farming is low. Of the three amberjack species, Japanese amberjack is at highest climate risk, owing to its cooler-water preferences and therefore higher thermal sensitivity if reared in cage conditions in Omani waters.

Overall climate risk is fairly low for red snapper, pompano, sobaity and goldlined seabreams (Table 5), typically farmed in sea cages; each of these Indo-Pacific species has low thermal risk in Omani waters, and as held in floating cages, are at low exposure to sea level rise or flooding, with limited evidence of disease risk. However, overall climate risk is high for gilthead seabream, relating to temperature affinities which are lower than typical sea temperatures in Oman. How different components of risk may differently affect the overall climate risk is exemplified by the northernmost governorate of Musandam where thermal risk to gilthead seabream is highest, but where risks from flooding or storm surge and from low-oxygen levels are lowest; hence overall climate risk for gilthead seabream aquaculture in Musandam emerges as lower than in other governorates.

Low climate risk was recorded for the two grouper species, yellowfin hind and greasy grouper. They have been proposed for culture in RAS, which are inherently less impacted by ambient temperature or other environmental conditions. Even so, both yellowfin hind and greasy grouper are well within their natural temperature ranges in Omani waters, and hence would experience little thermal stress if re-located outside. Moreover the fully isolated, RAS conditions make exposure to pathogens less likely.

Omani abalone and sea cucumber aquaculture are characterised as low risk, partly due to these species being within natural temperature ranges, especially within the governorates of Dhofar and Al Wusta, respectively, where these species would be cultivated.

For aquaculture of Atlantic salmon in Oman, a fully controlled and isolated RAS system is proposed, which would render salmon production relatively independent from ambient temperature or other environmental conditions; this does, however, necessitate full temperature control given salmon’s cold-water requirements. This also makes the risk from pathogen introduction low, provided original stock is safely sourced free of OIE listed diseases.

Table 6. Overall climate risks to aquaculture in Oman, as determined by the 4 component metrics (thermal sensitivity, exposure to flooding and storm surge, low-oxygen hazard, and disease vulnerability). Figures in bold indicate actual or planned developments.

		Overall climate risk					
Species group	**Species**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**
Seabreams	Gilthead seabream *Sparus aurata*	***0.33***	0.39	***0.46***	***0.49***	0.51	0.48
	Sobaity seabream *Sparidentex hasta*	***0.15***	0.21	***0.27***	***0.30***	0.33	0.30
	Goldlined seabream *Rhabdosargus sarba*	***0.17***	0.23	***0.29***	***0.32***	0.35	0.32
Groupers	Yellowfin hind (grouper) *Cephalopholis hemistiktos*	0.14	0.26	0.29	0.27	0.23	0.15
	Greasy grouper *Epinephelus tauvina*	0.23	0.35	0.37	0.36	0.32	0.24
Asian seabass	Asian seabass *Lates calcarifer*	0.23	0.29	0.36	0.39	0.42	0.38
Amber-jacks	Japanese amberjack *Seriola quinqueradiata*	0.35	0.41	***0.48***	***0.51***	***0.54***	0.51
	Greater amberjack *Seriola dumerili*	0.27	0.33	***0.40***	***0.43***	***0.46***	0.42
	Yellowtail amberjack *Seriola lalandi*	0.28	0.34	***0.41***	***0.44***	***0.47***	0.44
Cobia	Cobia *Rachycentron canadum*	0.26	0.32	0.39	0.42	0.44	0.41
Red snapper	Red snapper *Lutjanus malabaricus*	0.18	0.24	0.31	0.34	0.37	0.34
Pompano	Scubnose pompano *Trachinotus blochii*	0.18	0.24	0.30	0.33	0.36	0.33
Atlantic salmon	Atlantic salmon *Salmo salar*	0.28	0.40	0.45	0.50	0.49	0.40
Shrimp	Indian white prawn *Penaeus indicus*	0.18	0.36	0.39	***0.37***	***0.30***	0.18
	Whiteleg shrimp *Penaeus vannamei*	0.38	0.56	0.59	***0.57***	***0.51***	0.38
	Giant tiger prawn *Penaeus monodon*	0.38	0.56	0.59	***0.57***	***0.50***	0.38
Abalone	Oman abalone *Haliotis mariae*	0.24	0.36	0.41	0.42	0.40	***0.32***
Oyster	Hooded oyster *Saccostrea cucullata*	0.21	0.26	0.29	0.27	0.25	0.22
	Mangrove cupped oyster *Crassostrea rhizophorae*	0.23	0.29	0.31	0.29	0.28	0.24
Sea cucumber	Sandfish sea cucumber *Holothuria scabra*	0.17	0.36	0.41	0.41	***0.37***	0.24

4. Discussion

4.1. *Aquaculture CRA: identifying and communicating climate risk*

This aquaculture CRA, the first for Oman, demonstrates the application of a flexible framework that identifies climate risks to the aquaculture sector. Importantly the CRA identified the overall climate risk level for different species, culture types and governorates, and for each the predominant components of climate risk. Identifying specific risk factors is important for developing targeted adaptation measures and building climate resilience into the planned expansion of the sector (MAFW, 2019). The four risk components applied here were selected based on understanding climate impacts specific to the region, and different or additional risk factors could be applied within the same CRA framework to allow wide geographic application.

Despite the growing global importance of aquaculture, few country-level climate vulnerability (CVA) or risk assessments (CRA) have been carried out that specifically focussed on aquaculture. Among the first were Doubleday et al. (2013), who evaluated climate vulnerability for aquaculture in Southeast Australia, reporting that species cultured from wild spat were particularly at risk, as opposed to species where all stages of culture are in controlled conditions. For various European countries, a combined aquaculture CVA has also been carried out (Kamermans et al., 2020), and this showed that individual countries, from Norway and Finland in the north, to several Mediterranean countries in the south, differed substantially in risk levels and risk components to their aquaculture sectors – mirroring the findings within one country of the present study.

The systematic yet simple approach of the CRA has an important advantage: not only can key climate risks be rapidly identified – acknowledging that estimating uncertainties around risk metrics remains difficult, and that weighting of risk components can influence overall risk estimates (Monnereau et al., 2017) – but the presentation of the results can be easily explained. This is important for (early) communication of climate risk to wider audiences, which is required for actual implementation of adaptation action. Stakeholders, whose buy-in to adaptation is required, range from the aquaculture farmers themselves to government and scientists. Indeed, these three stakeholder groups were present when the online workshop was held in December 2020, aimed at identifying adaptation options based on this study. Participants contributed their experience and knowledge of aquaculture in the region, to discuss adaptation options in the context of each of the key climate risks identified here. Below, key risks for each culture type in Oman are discussed (based on the risk assessment), along with potential adaptation options to counter each risk factor (based on the workshop, and supplemented with published information).

4.2. *Key risks and adaptation options: shrimp farming*

A significant finding was that the highest climate risk is for shrimp farming yet this is seen as a cornerstone for future aquaculture development in Oman. Key risks identified are (1) disease vulnerability – with 9 OIE listed diseases for *Penaeus vannamei* and *P. monodon*, and the most severe of these also present in *P. indicus* – and (2) exposure to flooding. The latter relates to shrimp pond culture being associated with low-lying terrain close to the sea (Al-Yahyai et al., 2004; Peeler and Scott, 2018).

Adaptation actions to counter disease vulnerability in shrimp farms should especially focus on *minimising the risk of introductions*, i.e. reducing impacts rather than mitigating consequences as there are no effective treatments for the most serious shrimp diseases (Lightner, 2012). This highlights the importance of pathogen-free production and isolation from environmental sources. Notwithstanding the need for prevention, the wide geographic distribution of shrimp diseases may preclude the ability to entirely avoid disease outbreaks. In this case *preparedness to respond to outbreaks* is critical to mitigating consequences in the event that an outbreak occurs (Stentiford et al., 2012). Consequences of a disease outbreak can be further mitigated by spreading of shrimp production across many smaller sites, rather than a single or few very large sites, and localising and isolating disease outbreaks immediately, thus avoiding the entire sector from being impacted if an outbreak were to occur in one facility (McLean et al. 2011). As an alternative to pond culture, shrimp production in controllable indoor systems could be offered as a mitigation, with maintenance of water quality and exclusion of pathogens aided by novel biofloc technology (where carbon:nitrogen ratios in the system are balanced through microbial growth, so assimilating waste and enhancing water quality and shrimp feeding conditions: Ahmad et al., 2017).

To counter the high exposure to flood risk, adaptation options include strategic selection of farming sites where inundation risk is lower: this could be informed through flood risks maps (Al-Buloshi et al., 2014; Al-Awadhi et al., 2017). An alternative option is the construction of storm-surge proof infrastructure; elsewhere, increasing the heights of dikes was found to yield higher net benefits than other flood adaptation measures in shrimp ponds (Seekao and Pharino, 2018). Non-structural flood controls, such as early harvesting and shifting the crop calendar, are alternative measures for shrimp farmers who lack financial supports (Seekao and Pharino, 2018). Adaptation options aimed at mitigating consequences, include having insurance mechanisms in place that allow financial compensation of losses if flooding were to occur (Nguyen et al., 2021).

4.3. Key risks and adaptation options: cage farming for seabream and other fishes

Climate risk is also high for the species currently cultivated in greatest quantities in Oman – gilthead seabream. It is here driven by (1) thermal sensitivity and (2) low-oxygen hazard, and less by storm surge exposure or disease risk. Overall lower climate risk for gilthead seabream was found for northern than southern governorates, in spite of warmer mean temperatures further north (Table 6), and farming is already being achieved successfully there. Nevertheless, the thermal affinities of gilthead seabream for cooler temperatures than ambient conditions where currently farmed, indicate that production could be sub-optimal and current temperatures may be reaching an upper limit. This warrants investigation of the culture potential of related native species, sobaity and goldlined seabream, which are well within their thermal tolerance ranges in Omani waters (Pavlidis and Mylonas, 2011) and may be more resilient to future temperature increases. Sobaity seabream is cultured commercially in neighbouring United Arab Emirates (Basurco et al., 2011) indicating that culturing is possible.

Therefore, potential adaptation actions to limit thermal risk to seabream farming include investing in developing sobaity and goldlined seabream production and selection of gilthead seabream breeds that are more temperature-resistant (Soto et al., 2018). An alternative, technical option is the use of submersible cages (sunken to deeper, cooler waters) provided these are well aerated. Seasonal stocking of giltheads (part RAS and part net pen) may be another alternative to avoid the highest-risk periods.

The hazard of low-oxygen levels, greater in southern than northern governorates related with proximity to naturally occurring hypoxia zones is not restricted to gilthead seabream (e.g. Araújo-Luna et al., 2018) but equally relevant to other active-swimming fish species farmed in sea cages (Vigen, 2008). Low dissolved oxygen makes it also harder for fish held in sea cages to cope with high temperatures, and will reduce growth rates (Schurmann et al., 1991; Araújo-Luna et al., 2018). An adaptation option is having effective aeration systems in place to enhance oxygenation of cages during hypoxic periods (Berillis et al., 2016). Hypoxia risk could also be reduced through considering site selection at a national scale and locating sites further north where hypoxia events are less likely (Acharya and Panigrahi, 2016), or through analysis of local hydrodynamics to identify local-scale areas with reduced hypoxia risk.

Locating sites in sheltered bays in the north, as in Musandam, would also minimise risks from storm-related damages (Rafiq et al., 2015). An adaptation option aimed at improving preparedness, is having early warning systems in place to inform on upcoming hypoxia events, storm surges, or cyclones (Poulaine et al., 2018) that could trigger early harvesting or other response actions.

4.4. Key risks and adaptation options: RAS culture – groupers and salmon

For recirculating aquatic systems (RAS), climate risk is considered low (groupers) or fairly low (Atlantic salmon (Table 6). This is due to the highly controlled culture conditions, which decouple these systems from natural environmental fluctuations (Soto et al., 2018). Thus, thermal and low-oxygen related risks are low. Nevertheless, backup power systems are required as temperatures would soon be out of control if cooling failed in case of power shortages. Moreover, if RAS are situated close to sea they are still prone to inundation (Table 3), and there is the need to manage risks from disease vulnerability (Table 5).

RAS are, however, relatively expensive to run compared to cage or pond culture, so will mainly be suitable for species with high price per kg (as in groupers; FAO, 2018). For planned culture of Atlantic salmon, which have cold-water requirements (Elliott and Elliott, 2010), a single fully controlled and refrigerated RAS is being envisaged, however refrigeration costs can be expensive and may increase with increasing air temperatures. Therefore, adaptation options for salmon RAS could include cost-benefit analysis (Poulain et al., 2018) and consideration of species with less cooling requirement.

Managing risks of disease introduction for RAS is as important as with other culture types, even though the relative isolation from the marine environment reduces this risk. For Atlantic salmon, many OIE listed diseases exist in cooler climates, but provided that egg imports come from a source ensured to be free of OIE listed diseases, risk of further pathogen introduction will be very low, due to the absence of wild salmon from Omani waters (Peeler and Scott, 2018). For culture of groupers which do occur naturally in Oman, partial sourcing form wild stock is likely needed (Peeler and Scott, 2018). Adaptation options include having appropriate biosecurity, monitoring, and quarantine protocols in place (Poulain et al., 2018; Peeler and Scott, 2018).

4.5. Global relevance

With growing demand for seafood products globally but limits to what capture fisheries can sustainably supply, the importance of aquaculture to global nutritional demands is set to rise (Jennings et al., 2016; Little et al., 2016; FAO, 2020; Shepon et al., 2021). This is in line with aspirations in Oman to significantly expand aquaculture, to improve food security and local job opportunities while aiming to enhance sustainability in fisheries and reduce pressure on wild stocks (MAFW, 2019). With considerable climatic changes taking place and predicted for the region (ROPME, 2020), considering climate risk is important for planning developments within the sector.

Climate risk to aquaculture was broken down into four risk components – thermal sensitivity, flood exposure, low-oxygen hazard and disease vulnerability – assessed by species and (except disease vulnerability) by sub-region. This approach can be equally applied to evaluate climate risks to aquaculture for any other regional, national or sub-national location, although the components of climate risks may need to be adjusted for different locations, aquaculture species or culture systems. Many of the key risks identified here for Oman, such as high disease vulnerability and flooding exposure for shrimp culture, are also important elsewhere (e.g. Bangladesh: Hooper et al., 2020; Thailand: Seekao and Pharino, 2018), Moreover issues around thermal sensitivity as reported here for gilthead seabream and salmon, will also apply to other cold-water species, traditionally cultured at large scale in temperate countries but now beginning to be cultured in (sub)tropical regions (Pavlidis and Mylonas, 2011).

If extended to other countries, possible improvements are the inclusion of other sources of risk not accounted for in this study. Harmful algal blooms (HABs) are of particular concern for mussel and oyster culture, potentially rendering products toxic for human consumption (Callaway et al., 2012). Increasing frequency of HABs has been related to climate change interacting with eutrophication, and has been noted in coastal, warm-water ecosystems (Martínez et al., 2017). In Omani waters, occurrences of 'red tides' have become more frequent since monitoring began in the 1970s and have been linked to (wild) fish kill incidents (Al Gheilani ei al., 2011). If Oman's bivalve aquaculture, currently limited to experimental culture of hooded and mangrove cupped oyster, were to be expanded, early warning systems for HABs with communication to farms would be warranted (Poulain et al., 2018). Inclusion of a HAB risk component would also be recommended if a similar CRA were to be carried for a country where bivalve aquaculture is substantial (Theodorou et al., 2020; Mardones et al., 2020). Other risk components to be considered, include droughts or excessive rainfall; these factors are particularly important for freshwater aquaculture (Soto et al., 2018).

A screening-level risk assessment, such as carried out here provides guidance to scientists, resource managers and stakeholders on how climate change is expected to impact the physiology, life cycles and environment of aquaculture species and, ultimately, the way they are farmed. The study also highlights knowledge gaps in aquaculture research across a broad range of farming systems; outcomes from this assessment will focus attention towards the research required to underpin more detailed quantitative assessments of higher-risk culture types, species and sites and thus more optimal allocation of human and operational resources (Soho et al., 2018; Poulain et al., 2018; IPCC, 2019). Aquaculture production provides significant social, economic and nutritional benefits globally (Little et al., 2016; Shepon et al., 2021). The methods presented provide a broadly applicable, cost-effective and rapid approach not only to assess risk, but also to communicate risk to stakeholders and facilitate the necessary dialogue on pathways to adaptation – elements that make these methods relevant to many other regions around the world to build climate resilience in the global food chain.

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Supplementary Materials. Supplementary Table S1 provides an overview of all OIE listed diseases for Oman current and candidate aquaculture species, based on Peeler and Scott (2018). Supplementary Table S2 provides a break-down of all risk component scores by species and governorate, with all metrics re-scaled between 0 (low risk) and 1 (high risk), used to calculate overall climate risk.

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Supplementary Materials

Supplementary Table S1. Overview of OIE listed diseases for current or candidate Oman aquaculture species, based on the report by Peeler and Scott (2018) on development of aquatic animal health legislation for Oman. The total number of OIE listed diseases combines the viral, bacterial and fungal OIE listed diseases reported per species, where for each of the disease types, the fish or shellfish species potentially impacted are marked. The total *number of OIE listed diseases* per species is one of three component metrics, along with the metrics *concentration of production* and *local produce or import of broodstock*, used to quantify *overall disease vulnerability* (see Table 5).

		Viral												***Bacterial***			***Fungal***
Species	**Number of OIE listed diseases**	Epizootic ulcerative syndrome	Grouper iridoviral disease	Megalocytivirus	Red seabream iridoviral disease	Viral encephalopathy and retinopathy	Infectious hypodermal, haematopoietic necrosis	Infectious myonecrosis virus	Taura syndrome virus	Viral covert mortality disease of shrimps	White spot disease	Yellow head virus	Abalone herpesvirus	Abalone shrivelling syndrome associated	Acute hepatopancreas necrosis	Necrotising hepatopancreatitis	Xenohaliotis californiensis	Hepatopancreatic microsporidiosis caused by Enterocytozoon
Gilthead seabream *Sparus aurata*	1					1												
Sobaity seabream *Sparidentex hasta*	0																	
Goldlined seabream *Rhabdosargus sarba*	1			1														
Yellowfin hind *Cephalopholis hemistiktos*	0																	
Greasy grouper *Epinephelus tauvina*	3		1		1	1												
Asian seabass *Lates calcarifer*	3	1			1	1												
Japanese amberjack *Seriola quinqueradiata*	2				1	1												
Greater amberjack *Seriola dumerili*	2				1	1												
Yellowtail amberjack *Seriola lalandi*	2				1	1												
Cobia *Rachycentron canadum*	0																	
Red snapper *Lutjanus malabaricus*	0																	
Scubnose pompano *Trachinotus blochii*	0																	
Atlantic salmon *Salmo salar*	0 *)																	
Indian white prawn *Penaeus indicus*	1										1							
Whiteleg shrimp *Penaeus vannamei*	9						1	1	1	1	1	1			1	1		1
Giant tiger prawn *Penaeus monodon*	9						1	1	1	1	1	1			1	1		1
Oman abalone *Haliotis mariae*	3												1	1			1	
Hooded oyster *Saccostrea cucullata*	0																	
Mangrove cupped oyster *Crassostrea rhizophorae*	0																	
Sandfish sea cucumber *Holothuria scabra*	0																	

Supplementary Table S1. Full break-down of all risk component scores by species and governorate, with all component metrics re-scaled between 0 (low risk) and 1 (high risk), used in combination to calculate overall climate risk. Light to dark red colour shading is indicative of low to high risk.

	Thermal sensitivity						*Exposure to flooding and storm surge*						*Low-oxygen hazard*						*Disease vulnerability*	***Overall climate risk***					
Species	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**	**All governorates**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**
Gilthead seabream *Sparus aurata*	***1.00***	0.99	***0.98***	***0.84***	0.77	0.83	***0.03***	0.28	***0.29***	***0.28***	0.18	0.00	***0.18***	0.18	***0.45***	***0.73***	1.00	1.00	0.10	***0.33***	0.39	***0.46***	***0.49***	0.51	0.48
Sobaity seabream *Sparidentex hasta*	***0.37***	0.36	***0.35***	***0.21***	0.14	0.20	***0.03***	0.28	***0.29***	***0.28***	0.18	0.00	***0.18***	0.18	***0.45***	***0.73***	1.00	1.00	0.00	***0.15***	0.21	***0.27***	***0.30***	0.33	0.30
Goldlined seabream *Rhabdosargus sarba*	***0.35***	0.34	***0.33***	***0.19***	0.12	0.18	***0.03***	0.28	***0.29***	***0.28***	0.18	0.00	***0.18***	0.18	***0.45***	***0.73***	1.00	1.00	0.10	***0.17***	0.23	***0.29***	***0.32***	0.35	0.32
Yellowfin hind *Cephalopholis hemistiktos*	0.23	0.22	0.21	0.06	0.00	0.06	0.13	0.63	0.64	0.63	0.43	0.07	0.00	0.00	0.09	0.18	0.27	0.27	0.20	0.14	0.26	0.29	0.27	0.23	0.15
Greasy grouper *Epinephelus tauvina*	0.29	0.28	0.26	0.12	0.06	0.11	0.13	0.63	0.64	0.63	0.43	0.07	0.00	0.00	0.09	0.18	0.27	0.27	0.50	0.23	0.35	0.37	0.36	0.32	0.24
Asian seabass *Lates calcarifer*	0.31	0.30	0.29	0.15	0.08	0.14	0.03	0.28	0.29	0.28	0.18	0.00	0.18	0.18	0.45	0.73	1.00	1.00	0.40	0.23	0.29	0.36	0.39	0.42	0.38
Japanese amberjack *Seriola quinqueradiata*	0.70	0.68	***0.67***	***0.53***	***0.47***	0.52	0.03	0.28	***0.29***	***0.28***	***0.18***	0.00	0.18	0.18	***0.45***	***0.73***	***1.00***	1.00	0.50	0.35	0.41	***0.48***	***0.51***	***0.54***	0.51
Greater amberjack *Seriola dumerili*	0.37	0.36	***0.35***	***0.21***	***0.14***	0.20	0.03	0.28	***0.29***	***0.28***	***0.18***	0.00	0.18	0.18	***0.45***	***0.73***	***1.00***	1.00	0.50	0.27	0.33	***0.40***	***0.43***	***0.46***	0.42
Yellowtail amberjack *Seriola lalandi*	0.41	0.40	***0.39***	***0.25***	***0.18***	0.24	0.03	0.28	***0.29***	***0.28***	***0.18***	0.00	0.18	0.18	***0.45***	***0.73***	***1.00***	1.00	0.50	0.28	0.34	***0.41***	***0.44***	***0.47***	0.44
Cobia *Rachycentron canadum*	0.32	0.31	0.30	0.16	0.09	0.15	0.03	0.28	0.29	0.28	0.18	0.00	0.18	0.18	0.45	0.73	1.00	1.00	0.50	0.26	0.32	0.39	0.42	0.44	0.41
Red snapper *Lutjanus malabaricus*	0.31	0.30	0.29	0.15	0.09	0.14	0.03	0.28	0.29	0.28	0.18	0.00	0.18	0.18	0.45	0.73	1.00	1.00	0.20	0.18	0.24	0.31	0.34	0.37	0.34
Scubnose pompano *Trachinotus blochii*	0.29	0.28	0.27	0.13	0.06	0.12	0.03	0.28	0.29	0.28	0.18	0.00	0.18	0.18	0.45	0.73	1.00	1.00	0.20	0.18	0.24	0.30	0.33	0.36	0.33
Atlantic salmon *Salmo salar*	0.50	0.50	0.50	0.50	0.50	0.50	0.13	0.63	0.64	0.63	0.43	0.07	0.09	0.09	0.27	0.45	0.64	0.64	0.40	0.28	0.40	0.45	0.50	0.49	0.40
Indian white prawn *Penaeus indicus*	0.28	0.27	0.26	***0.12***	***0.05***	0.11	0.23	0.97	1.00	***0.98***	***0.69***	0.13	0.00	0.00	0.09	***0.18***	***0.27***	0.27	0.20	0.18	0.36	0.39	***0.37***	***0.30***	0.18
Whiteleg shrimp *Penaeus vannamei*	0.29	0.28	0.27	***0.13***	***0.06***	0.12	0.23	0.97	1.00	***0.98***	***0.69***	0.13	0.00	0.00	0.09	***0.18***	***0.27***	0.27	1.00	0.38	0.56	0.59	***0.57***	***0.51***	0.38
Giant tiger prawn *Penaeus monodon*	0.29	0.28	0.27	***0.13***	***0.06***	0.12	0.23	0.97	1.00	***0.98***	***0.69***	0.13	0.00	0.00	0.09	***0.18***	***0.27***	0.27	1.00	0.38	0.56	0.59	***0.57***	***0.50***	0.38
Oman abalone *Haliotis mariae*	0.44	0.43	0.42	0.28	0.21	***0.27***	0.13	0.63	0.64	0.63	0.43	***0.07***	0.09	0.09	0.27	0.45	0.64	***0.64***	0.30	0.24	0.36	0.41	0.42	0.40	***0.32***
Hooded oyster *Saccostrea cucullata*	0.29	0.28	0.27	0.13	0.06	0.12	0.03	0.28	0.29	0.28	0.18	0.00	0.00	0.00	0.09	0.18	0.27	0.27	0.50	0.21	0.26	0.29	0.27	0.25	0.22
Cupped oyster *Crassostrea rhizophorae*	0.37	0.36	0.35	0.21	0.15	0.20	0.03	0.28	0.29	0.28	0.18	0.00	0.00	0.00	0.09	0.18	0.27	0.27	0.50	0.23	0.29	0.31	0.29	0.28	0.24
Sandfish sea cucumber *Holothuria scabra*	0.27	0.26	0.25	0.11	***0.05***	0.10	0.23	0.97	1.00	0.98	***0.69***	0.13	0.09	0.09	0.27	0.45	***0.64***	0.64	0.10	0.17	0.36	0.41	0.41	***0.37***	0.24

Table 1. Overview of species included based on current and potential future importance for Oman aquaculture, including information on current or proposed culture type and projected production (based on Peeler and Scott 2018; supplementary data for cobia taken from Prins 2015). Price per kg and projected value are expressed in 2018-US$ and based on mean global aquaculture price (from FAO Fisheries and Aquaculture Statistics). Projected value by 2023 is based on projected production (Peeler and Scott 2018). Figures on future production should only be seen as indicative of proposed future development.

Species group	**Species**	**Type of culture**	**Projected production (t)**	**Price/kg (US$)**	**Projected value (US$)**	**Regions**
Seabreams	Gilthead seabream *Sparus aurata*	Marine cages; RAS	15500	$4.73	$143,500,000	Musandam, Muscat, Ash Sharqiyah
	Sobaity seabream *Sparidentex hasta*			$13.25		Musandam, Muscat, Ash Sharqiyah
	Goldlined seabream *Rhabdosargus sarba*			$9.79		Musandam, Muscat, Ash Sharqiyah
Groupers	Yellowfin hind (grouper) *Cephalopholis hemistiktos*	RAS	9000	$18.59	$167,300,000	not specified
	Greasy grouper *Epinephelus tauvina*			$18.59		not specified
Asian seabass	Asian seabass (Barramundi) *Lates calcarifer*	Marine cages	2500	$4.52	$11,300,000	not specified
Amberjacks	Japanese amberjack *Seriola quinqueradiata*	Marine cages	2000	$7.77	$19,660,000	Muscat, Ash Sharqiyah, Al Wusta
	Greater amberjack *Seriola dumerili*			$9.10		Muscat, Ash Sharqiyah, Al Wusta
	Yellowtail amberjack *Seriola lalandi*			$12.62		Muscat, Sharqiyah, Al Wusta
Cobia	Cobia *Rachycentron canadum*	Marine cages		$2.83		not specified
Red snapper	Red snapper (Hamra) *Lutjanus malabaricus*	Marine cages	100	$6.62	$662,000	not specified

Pompano	Scubnose pompano *Trachinotus blochii*	Marine cages	100	$4.77	$477,000	not specified
Atlantic salmon	Atlantic salmon *Salmo salar*	RAS	20000	$7.07	$141,400,000	not specified
Shrimp	Indian white prawn *Penaeus indicus*	Shrimp ponds	130000	$4.92	$840,700,000	Ash Sharqiyah, Al Wusta
	Whiteleg shrimp *Penaeus vannamei*			$6.09		Ash Sharqiyah, Al Wusta
	Giant tiger prawn *Penaeus monodon*			$8.39		Ash Sharqiyah, Al Wusta
Abalone	Oman abalone *Haliotis mariae*	RAS and restocking	2000	$11.30	$22,600,000	Dhofar
Oyster	Hooded oyster *Saccostrea cucullata*			$10.31		not specified
	Mangrove cupped oyster *Crassostrea rhizophorae*			$1.00		not specified
Sea cucumber	Sandfish sea cucumber *Holothuria scabra*	Marine ponds and raceways restocking	2000	$5.27	$10,540,000	Al Wusta

Table 2. Risk from *thermal sensitivity*. The 'maximum preferred temperatures' (TP90) for 20 target or candidate aquaculture species in Oman, as well as – shown separately for each governorate – the 'thermal safety margins.' Annual mean SST for coastal waters adjacent to each governorate is indicated (bottom of table). Thermal safety margins are defined as the difference between a species' TP90 and governorate's SST, in °C (TP90 – SST), colour-coded from blue to red (low to high risk). Figures in bold indicate actual or planned developments. *Note:* for Atlantic salmon, which in Oman is planned to be cultured in fully temperature-controlled RAS, thermal sensitivity margins are shown but no risk-based colour-shading applied.

			Species' thermal sensitivity margin by governorate (annual mean SST in °C above TP90)					
Species group	**Species**	**Maximum preferred temperature (TP90, °C)**	**Musan-dam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**
Seabreams	Gilthead seabream *Sparus aurata*	21.44	***-7.42***	-7.31	***-7.18***	***-5.66***	-4.96	-5.57

	Sobaity seabream *Sparidentex hasta*	28.24	***-0.62***	-0.51	***-0.38***	***1.14***	1.84	1.23
	Goldlined seabream *Rhabdosargus sarba*	28.43	***-0.43***	-0.32	***-0.19***	***1.33***	2.03	1.42
Groupers	Yellowfin hind (grouper) *Cephalopholis hemistiktos*	29.77	0.91	1.02	1.15	2.67	3.37	2.76
	Greasy grouper *Epinephelus tauvina*	29.15	0.29	0.40	0.53	2.05	2.75	2.14
Asian seabass	Asian seabass *Lates calcarifer*	28.89	0.03	0.14	0.27	1.79	2.49	1.88
Amberjacks	Japanese amberjack *Seriola quinqueradiata*	24.73	-4.13	-4.02	***-3.89***	***-2.37***	***-1.67***	-2.28
	Greater amberjack *Seriola dumerili*	28.23	-0.63	-0.52	***-0.39***	***1.13***	***1.83***	1.22
	Yellowtail amberjack *Seriola lalandi*	27.79	-1.07	-0.96	***-0.83***	***0.69***	***1.39***	0.78
Cobia	Cobia *Rachycentron canadum*	28.77	-0.09	0.02	0.15	1.67	2.37	1.76
Red snapper	Red snapper *Lutjanus malabaricus*	28.84	-0.02	0.09	0.22	1.74	2.44	1.83
Pompano	Scubnose pompano *Trachinotus blochii*	29.12	0.26	0.37	0.50	2.02	2.72	2.11
Atlantic salmon	Atlantic salmon *Salmo salar*	12.77	(-16.09)	(-15.98)	(-15.85)	(-14.33)	(-13.63)	(-14.24)
Shrimp	Indian white prawn *Penaeus indicus*	29.18	0.32	0.43	0.56	***2.08***	***2.78***	2.17
	Whiteleg shrimp *Penaeus vannamei*	29.08	0.22	0.33	0.46	***1.98***	***2.68***	2.07
	Giant tiger prawn *Penaeus monodon*	29.10	0.24	0.35	0.48	***2.00***	***2.70***	2.09
Abalone	Oman abalone *Haliotis mariae*	27.50	-1.36	-1.25	-1.12	0.40	1.10	***0.49***
Oyster	Hooded oyster *Saccostrea cucullata*	29.12	0.26	0.37	0.50	2.02	2.72	2.11
	Mangrove cupped oyster *Crassostrea rhizophorae*	28.19	-0.67	-0.56	-0.43	1.09	1.79	1.18

Sea cucumber	Sandfish sea cucumber *Holothuria scabra*	29.27	0.41	0.52	0.65	2.17	***2.87***	2.26
Annual mean SST by governorate (°C)			**28.86**	**28.75**	**28.62**	**27.10**	**26.40**	**27.01**

Table 3. Relative exposure to *flooding and storm surge*, assessed for Oman key aquaculture species or species groups by governorate. For each species, *sensitivity to flooding* is scored (1 low, 3 high) based on culture type and biological characteristics. For each governorate, *flooding hazard* is scored (bottom row) based on the area predicted to be flooded if mean sea level rises by 0.2 m (Al-Buloshi et al., 2014) per km of coastline. Relative exposure per species and governorate is then calculated as *sensitivity x hazard*. Colour-shading indicates low (light) to high exposure (dark red). Figures in bold indicate actual or planned developments.

		Species' relative exposure by governorate					
Species or species group	**Sensitivity to flooding**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**
Seabreams	1	***0.07***	0.25	***0.26***	***0.25***	0.18	0.05
Groupers	2	0.14	0.50	0.51	0.50	0.36	0.10
Asian seabass	1	0.07	0.25	0.26	0.25	0.18	0.05
Amberjacks	1	0.07	0.25	***0.26***	***0.25***	***0.18***	0.05
Cobia	1	0.07	0.25	0.26	0.25	0.18	0.05
Red snapper	1	0.07	0.25	0.26	0.25	0.18	0.05
Pompano	1	0.07	0.25	0.26	0.25	0.18	0.05
Atlantic salmon	2	0.14	0.50	0.51	0.50	0.36	0.10
Shrimp	3	0.21	0.75	0.77	***0.75***	***0.54***	0.14
Oman abalone	2	0.14	0.50	0.51	0.50	0.36	***0.10***
Oysters	1	0.07	0.25	0.26	0.25	0.18	0.05
Sea cucumber	3	0.21	0.75	0.77	0.75	***0.54***	0.14
Inundated area (km²) with sea level rise 0.2 m		35	60	50	120	105	25
Coastline (km)		495	241	196	480	584	523

Flooding hazard: inundated area (km^2) per km of coastline with sea level rise 0.2 m	0.07	0.25	0.26	0.25	0.18	0.05

Table 4. Relative hazard from *low-oxygen levels in seawater*, assessed for Oman key aquaculture species or species groups by governorate. For each species, *sensitivity to low-oxygen risk* is scored (1 low, 3 high) based on culture type and biological characteristics. For each governorate, *low-oxygen hazard* is scored (1 low, 4 high), based on geographical patterns in duration and intensity of low-oxygen conditions linked to the Arabian Sea oxygen minimum zone (Acharya and Panigrahi, 2016; Piontkovski and Queste, 2016; Queste et al., 2018). Relative hazard per species and governorate is then calculated as *sensitivity x hazard*. Colour-shading indicates low (light) to high hazard (dark red).

		Species' relative hazard by governorate					
Species or species group	**Sensitivity to low-oxygen risk**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**
Seabreams	3	***3***	3	***6***	***9***	12	12
Groupers	1	1	1	2	3	4	4
Asian seabass	3	3	3	6	9	12	12
Amberjacks	3	3	3	***6***	***9***	***12***	12
Cobia	3	3	3	6	9	12	12
Red snapper	3	3	3	6	9	12	12
Pompano	3	3	3	6	9	12	12
Atlantic salmon	2	2	2	4	6	8	8
Shrimp	1	1	1	2	***3***	***4***	4
Oman abalone	2	2	2	4	6	8	***8***
Oysters	1	1	1	2	3	4	4
Sea cucumber	2	2	2	4	6	***8***	8
Low-oxygen hazard by governorate		1	1	2	3	4	4

Table 5. Proxies for *vulnerability to disease* (right-most column) for Oman aquaculture species, calculated as the average of three risk factors: (a) total number of OIE listed diseases per species (Peeler and Scott, 2018); (b) origin of broodstock, whether locally produced or imported; and (c) concentration of production in few or many farms. Number of OIE listed diseases combines the viral, bacterial and fungal diseases listed in Supplementary Table S1. Ranking of broodstock-related risk: 1, all stock derived from local broodstock (low risk of pathogen import); 2, stock derived partly from local, partly from imported broodstock (medium risk); 3, fully derived from imported broodstock (high risk of pathogen import). Risk ranking of concentration of production: 1, production spread over at least 5 farms (risk spread, hence lower); 2, production in 2-4 farms; 3, production in 1 farm only (risk concentrated, hence higher). Colour-shading indicates low to high risk.

Species group	**Species**	**Number of OIE listed diseases**	**Local produce or import of broodstock**	**Concen-tration of production**	***Overall vulnerability to disease***
Seabreams	Gilthead seabream *Sparus aurata*	1	1	1	**1.0**
	Sobaity seabream *Sparidentex hasta*	0	1	1	**0.7**
	Goldlined seabream *Rhabdosargus sarba*	1	1	1	**1.0**
Groupers	Yellowfin hind (grouper) *Cephalopholis hemistiktos*	0	2	2	**1.3**
	Greasy grouper *Epinephelus tauvina*	3	2	2	**2.3**
Asian seabass	Asian seabass *Lates calcarifer*	3	1	2	**2.0**
Amber-jacks	Japanese amberjack *Seriola quinqueradiata*	2	3	2	**2.3**
	Greater amberjack *Seriola dumerili*	2	3	2	**2.3**
	Yellowtail amberjack *Seriola lalandi*	2	3	2	**2.3**
Cobia	Cobia *Rachycentron canadum*	0		n.a.	**n.a.**
Red snapper	Red snapper *Lutjanus malabaricus*	0	1	3	**1.3**

Pompano	Scubnose pompano *Trachinotus blochii*	0	1	3	**1.3**
Atlantic salmon	Atlantic salmon *Salmo salar*	0 *)	1	3	**2.0**
Shrimp	Indian white prawn *Penaeus indicus*	1	2	1	**1.3**
	Whiteleg shrimp *Penaeus vannamei*	9	2	1	**4.0**
	Giant tiger prawn *Penaeus monodon*	9	2	1	**4.0**
Abalone	Oman abalone *Haliotis mariae*	3	1	1	**1.7**
Oyster	Hooded oyster *Saccostrea cucullata*	0		n.a.	**n.a.**
	Mangrove cupped oyster *Crassostrea rhizophorae*	0		n.a.	**n.a.**
Sea cucumber	Sandfish sea cucumber *Holothuria scabra*	0	1	2	**1.0**

Table 6. Overall climate risks to aquaculture in Oman, as determined by the 4 component metrics (thermal sensitivity, exposure to flooding and storm surge, low-oxygen hazard, and disease vulnerability). Figures in bold indicate actual or planned developments.

		Overall climate risk					
Species group	**Species**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**
Seabreams	Gilthead seabream *Sparus aurata*	***0.33***	0.39	***0.46***	***0.49***	0.51	0.48
	Sobaity seabream *Sparidentex hasta*	***0.15***	0.21	***0.27***	***0.30***	0.33	0.30

	Goldlined seabream *Rhabdosargus sarba*	***0.17***	0.23	***0.29***	***0.32***	0.35	0.32
Groupers	Yellowfin hind (grouper) *Cephalopholis hemistiktos*	0.14	0.26	0.29	0.27	0.23	0.15
	Greasy grouper *Epinephelus tauvina*	0.23	0.35	0.37	0.36	0.32	0.24
Asian seabass	Asian seabass *Lates calcarifer*	0.23	0.29	0.36	0.39	0.42	0.38
Amber-jacks	Japanese amberjack *Seriola quinqueradiata*	0.35	0.41	***0.48***	***0.51***	***0.54***	0.51
	Greater amberjack *Seriola dumerili*	0.27	0.33	***0.40***	***0.43***	***0.46***	0.42
	Yellowtail amberjack *Seriola lalandi*	0.28	0.34	***0.41***	***0.44***	***0.47***	0.44
Cobia	Cobia *Rachycentron canadum*	0.26	0.32	0.39	0.42	0.44	0.41
Red snapper	Red snapper *Lutjanus malabaricus*	0.18	0.24	0.31	0.34	0.37	0.34
Pompano	Scubnose pompano *Trachinotus blochii*	0.18	0.24	0.30	0.33	0.36	0.33
Atlantic salmon	Atlantic salmon *Salmo salar*	0.28	0.40	0.45	0.50	0.49	0.40
Shrimp	Indian white prawn *Penaeus indicus*	0.18	0.36	0.39	***0.37***	***0.30***	0.18
	Whiteleg shrimp *Penaeus vannamei*	0.38	0.56	0.59	***0.57***	***0.51***	0.38
	Giant tiger prawn *Penaeus monodon*	0.38	0.56	0.59	***0.57***	***0.50***	0.38
Abalone	Oman abalone *Haliotis mariae*	0.24	0.36	0.41	0.42	0.40	***0.32***
Oyster	Hooded oyster *Saccostrea cucullata*	0.21	0.26	0.29	0.27	0.25	0.22
	Mangrove cupped oyster *Crassostrea rhizophorae*	0.23	0.29	0.31	0.29	0.28	0.24
Sea cucumber	Sandfish sea cucumber *Holothuria scabra*	0.17	0.36	0.41	0.41	***0.37***	0.24